DARK ENERGY
SURVEY

The Photometric Calibration of the DES

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Joint DOE/NSF Review of DES
29-31 January 2008

Basic Observing Strategy

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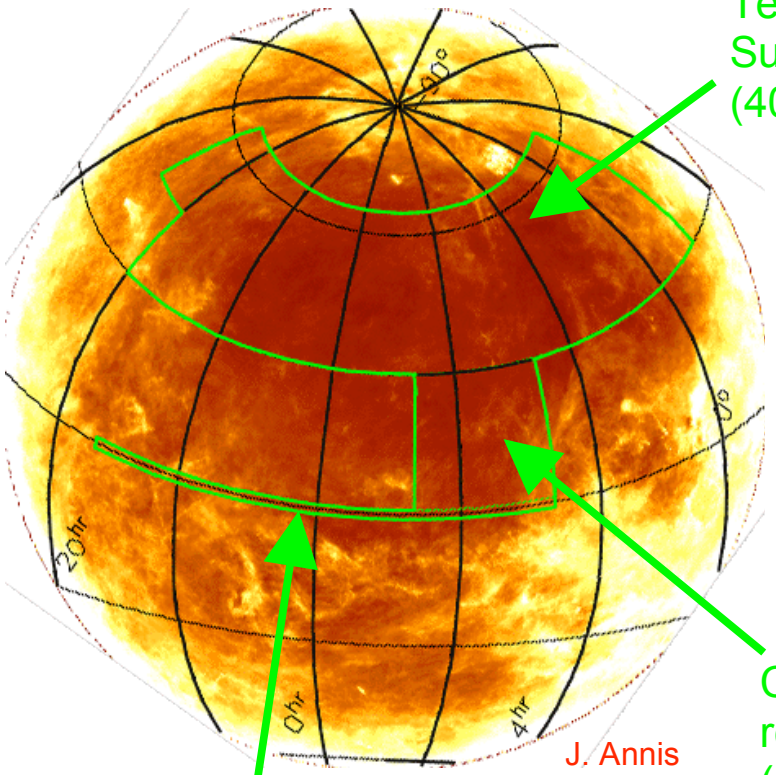
Observing Strategy

- 100 sec exposures
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *iZ* in bright time
  - Y filter
- Multiple tilings/overlaps to optimize photometric calibrations
- 2 survey tilings/filter/year
- All-sky photometric accuracy
  - Requirement: 2%
  - Goal: 1%

Survey Area



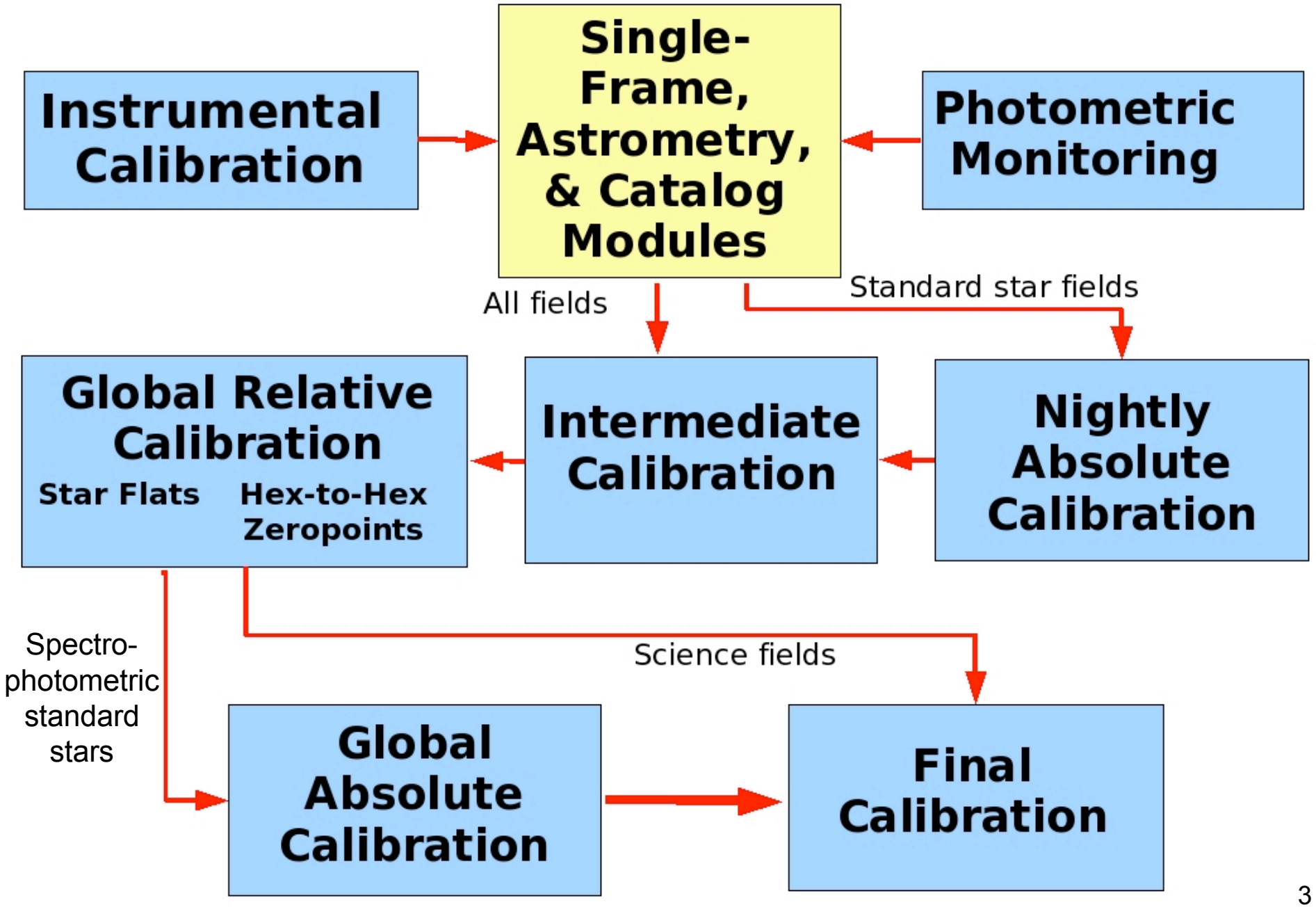
Overlap with South Pole Telescope Survey (4000 sq deg)

Connector region (800 sq deg)

Overlap with SDSS equatorial Stripe 82 for calibration (200 sq deg)

Total Area: 5000 sq deg

DES Calibrations Flow Diagram (v2)



Photometric Monitoring

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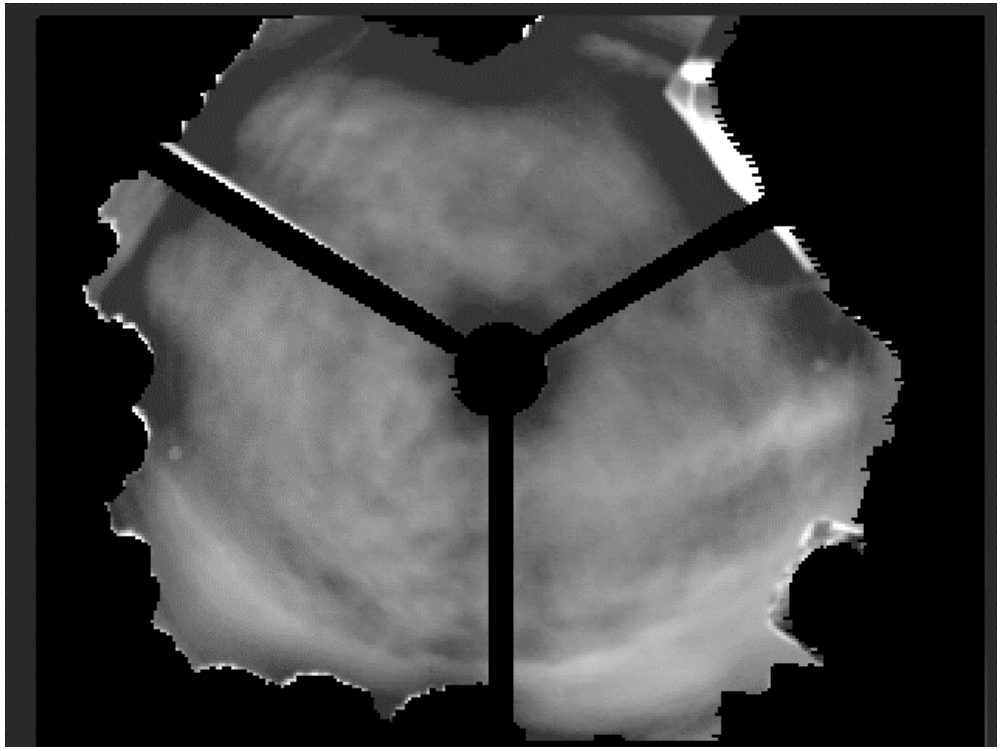
10 micron All-Sky Camera

- Provides real-time estimates of sky conditions for survey strategy
- Provides a measure of the photometric quality of an image for off-line processing
- Detects even light cirrus under a full range of moon phases (no moon to full moon)



APO 10 micron all-sky camera

For more details, see the presentation on the Sky Camera during the SISPI Breakout Session.

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Nightly Absolute Calibration

(Evolving) Standard Star Observation Strategy:

- Observe 3 standard star fields, each at a different airmass (*X*=1-2), between nautical (12°) and astronomical (18°) twilight (evening and morning).
- Observe up to 3 more standard fields (at various airmasses) throughout the night
- Also can observe standard star fields when sky is photometric but seeing is too poor for science imaging (seeing > 1.1 arcsec)
- Use fields with multiple standard stars
- Keep an eye on the photometricity monitors

Nightly Absolute Calibration Strategy:

- Calibrate to the DES *griZY* "natural" system
  - In theory, no system response color terms in the photometric equations
  - In practice, there may be small (1-2%) color terms over the focal plane and over time
  - Avoids coupling science images obtained in different filters (to first order)
- Use *u'g'r'i'z'* and *ugriz* standards transformed to the DES *griZ* "natural" system
  - SDSS *g'r'i'(z')* and *gri(z)* are similar to DES *griZ*, so transformations should be well behaved
- Use or create Y band standards
  - UKIDSS observations in SDSS Stripe 82? VHS Y-band standards?
  - Synthetic magnitudes of hot white dwarfs in SDSS Stripe 82?

Nightly Absolute Calibration: SDSS Stripe 82 *ugriz* Standards

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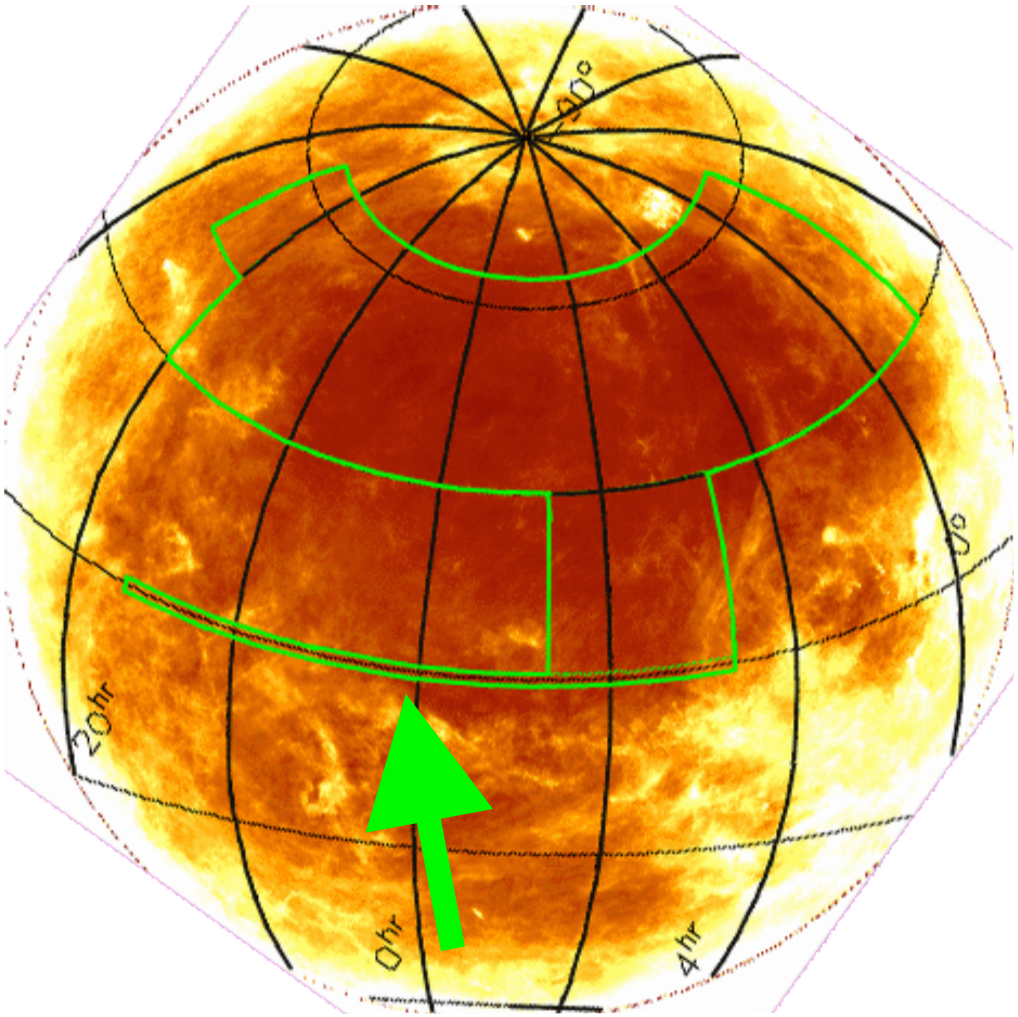


Already part of the DES survey strategy.

Readily observable at a range of airmasses throughout most nights during the DES program.

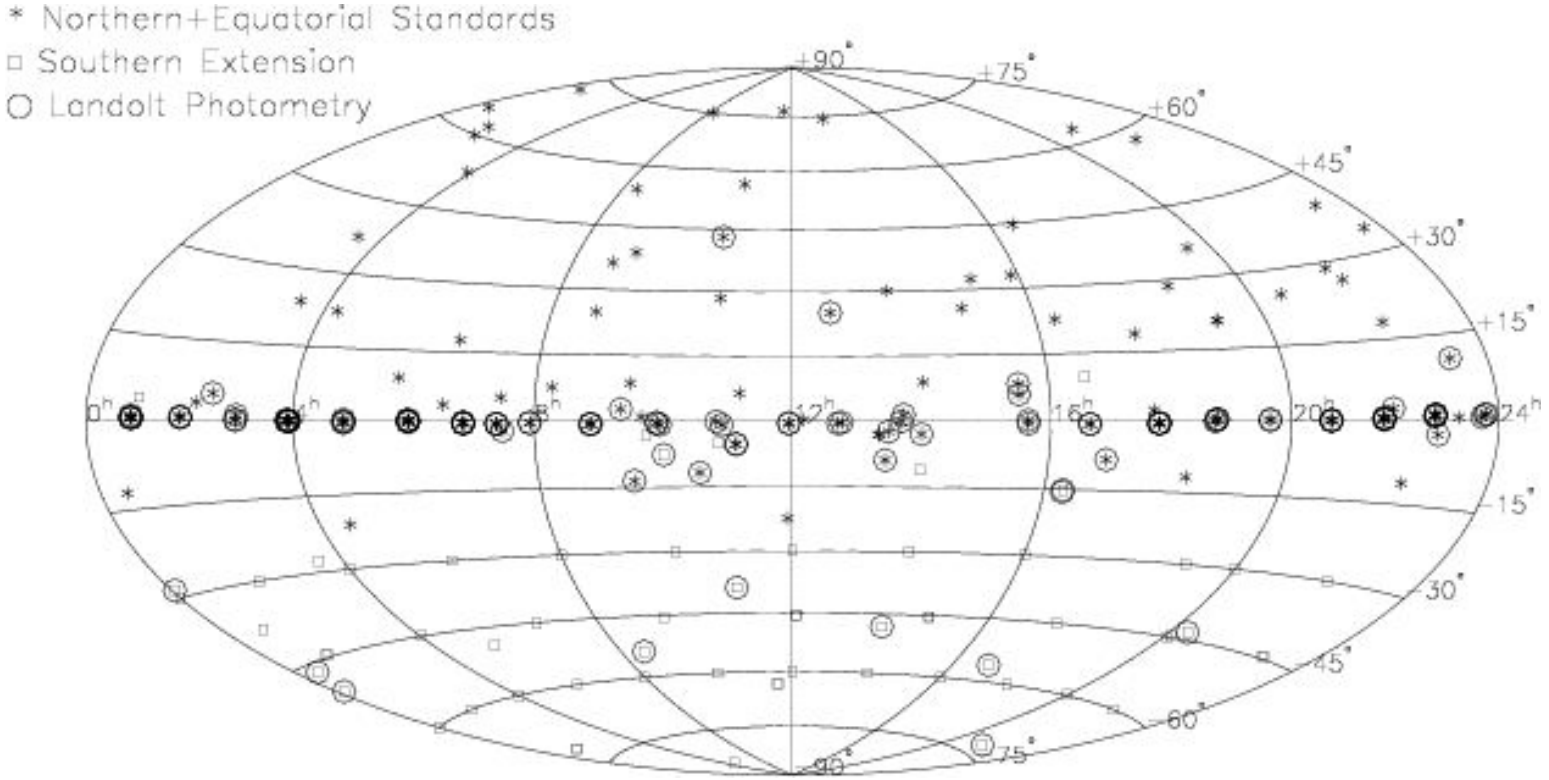
2.5° wide (compares favorably with DECam's FOV (≈2.2°).

Value-added catalogue of tertiary standards is being made

- Area of Stripe 82 has been observed by SDSS > 10x under photometric conditions
- ~ 1 million tertiary SDSS *ugriz* standards (r = 14.5 - 21)!
- ~ 4000 per sq deg (on average)
- See Ivezić et al. (2007)

Nightly Absolute Calibration: Southern *u'g'r'i'z'* Standards

DARK ENERGY SURVEY



- Smith, Allam, Tucker, Stute, Rodgers, Stoughton
- 13.5' x 13.5' fields, typically tens of stds. per field
- *r* = 9 - 18, ~60 fields, ~16,000 standards
- stars as bright as r≈13 can likely be observed by DECam with 5+ second exposures under conditions of poor seeing or with de-focusing (FWHM=1.5").
- http://www-star.fnal.gov/Southern_ugriz/

(Others: SkyMapper standards? VST OmegaCam standards? Stars from PanSTARRS-1 3π survey?)

Nightly Absolute Calibration: The Photometric Standards Module (PSM)

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- The PSM is basically a big least squares solver, fitting the observed magnitudes of a set of standard stars to their "true" magnitudes via a simple model (photometric equation); e.g.:

$$m_{inst} - m_{std} = a_n + kX \qquad (1)$$

  - m_{inst} is the instrumental magnitude, $m_{inst} = -2.5log(counts/sec)$ (input)
  - m_{std} is the standard ("true") magnitude of the standard star (input)
  - a_n is the photometric zeropoint for CCD n (n = 1-62) (output)
  - k is the first-order extinction (input/output)
  - X is the airmass (input)

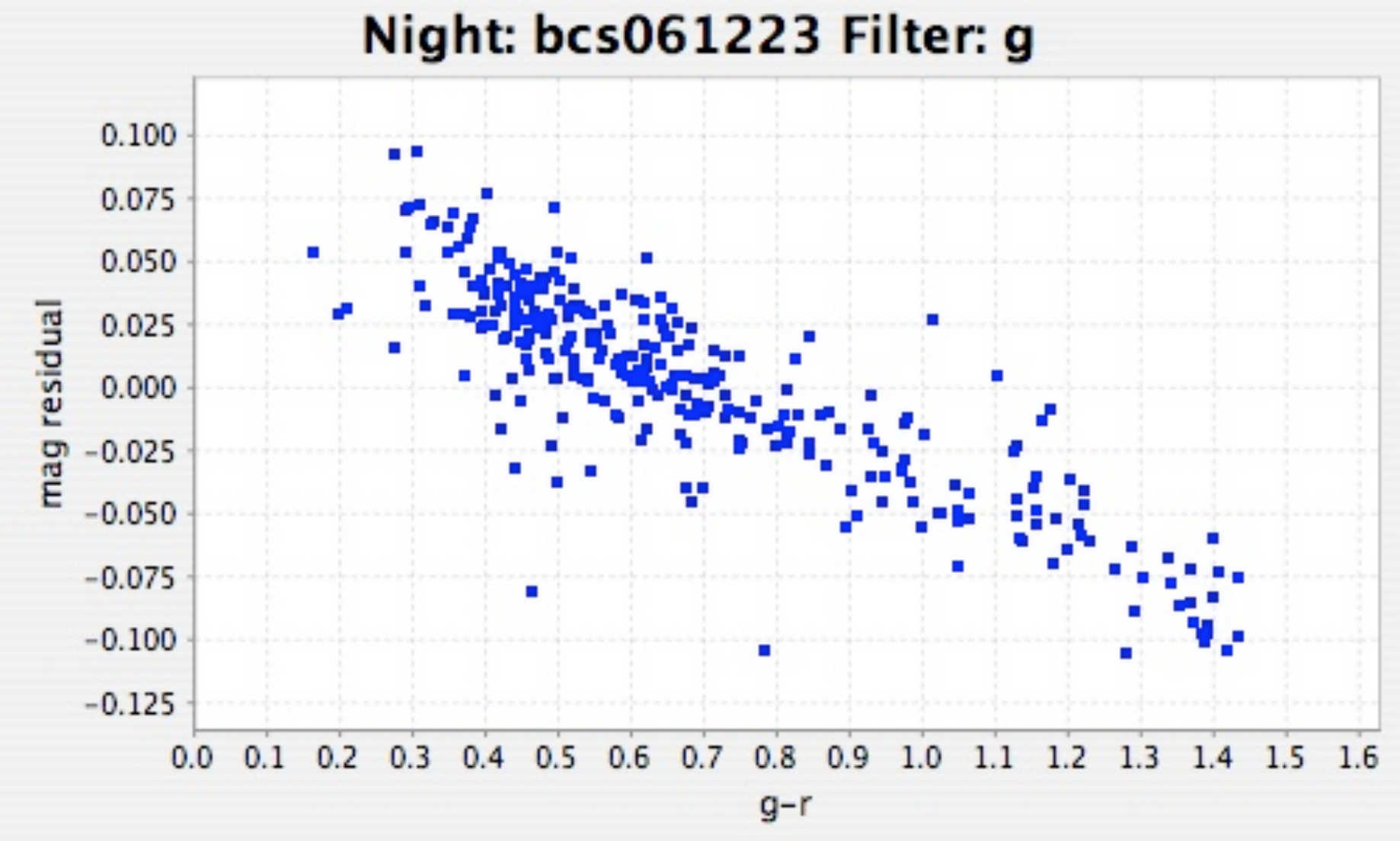
- A refinement: add an instrumental color term for each CCD to account for small differences between the standard star system and the natural system of that CCD:

$$m_{inst} - m_{std} = a_n + b_n \times (stdColor - stdColor_0) + kX \qquad (2)$$

  - b_n is the instrumental color term coefficient for CCD n (n = 1-62) (input/output)
  - $stdColor$ is a color index, e.g., $(g-r)$ (input)
  - $stdColor_0$ is a constant (a fixed reference value for that passband) (input)
  - DES calibrations will be in the DECam natural system
    - Even if SDSS Stripe 82 *ugriz* and Smith et al. Southern *u'g'r'i'z'* standards are "pre-transformed" to the DES system, eq. 2 is still useful for track changes in DECam instrumental response across the focal plane and over time

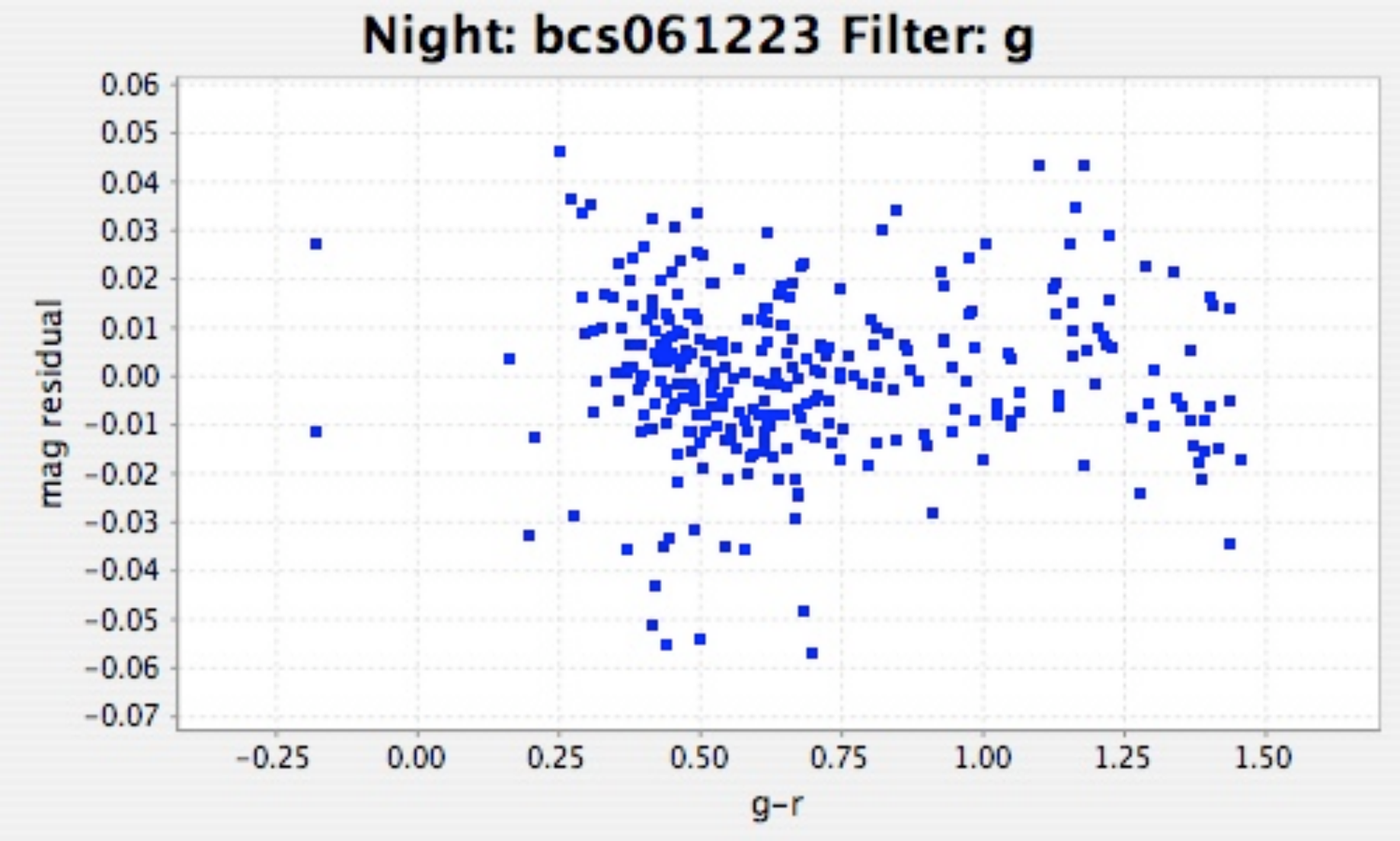
Blanco Cosmology Survey, Fixing *b*'s to 0 (rms=0.041 mag, χ^2/ν=4.24)

DARK ENERGY SURVEY



Blanco Cosmology Survey, Solving for *b*'s (rms=0.017 mag, χ^2/ν=0.74)

DARK ENERGY SURVEY



Global Relative Calibrations: Hex-to-Hex Zeropoint Offsets

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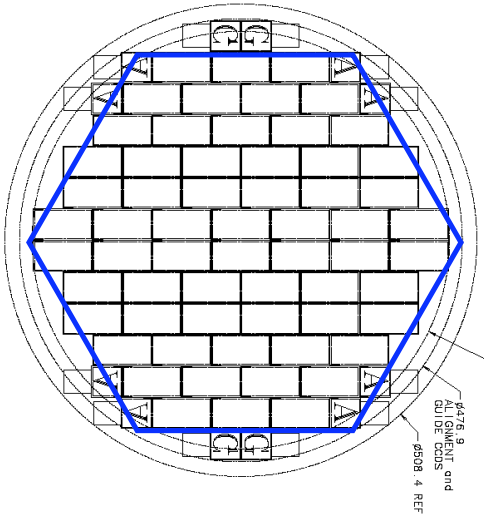
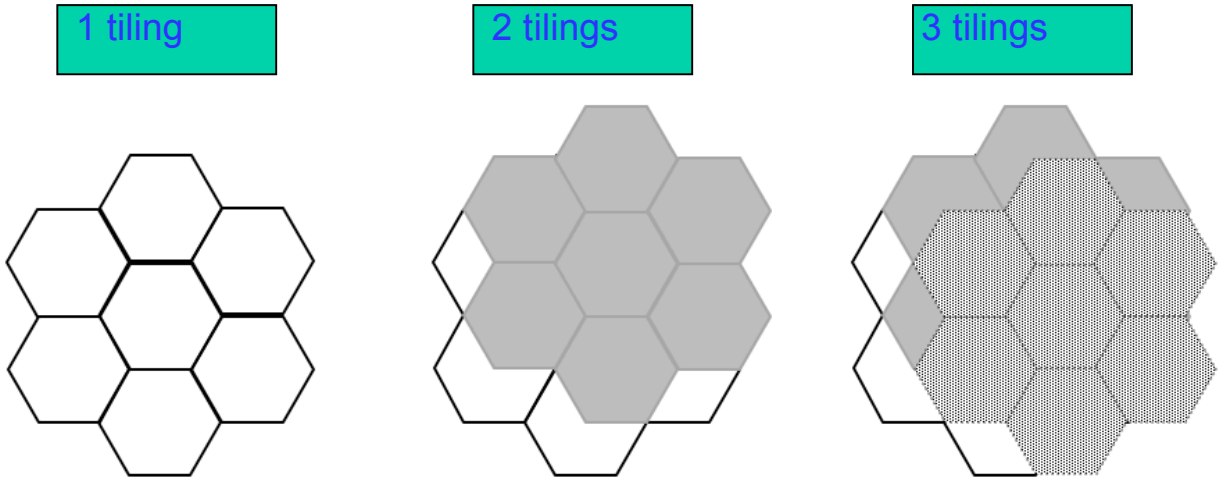
- We cover the sky twice per year per filter. This is called tiling.
- It takes ~1700 hexes to tile the whole survey area.

Recipe:

- Tile the plane
- Then, tile the plane with hex offset half hex over and up
- This gives 30% overlap with three hexagons
- Repeat, with different offsets
- Large overlaps provide very robust hex-to-hex relative calibrations
- Similar to PanStarrs strategy



DECam Focal Plane: "The Hex"



Global Relative Calibrations: Star Flats

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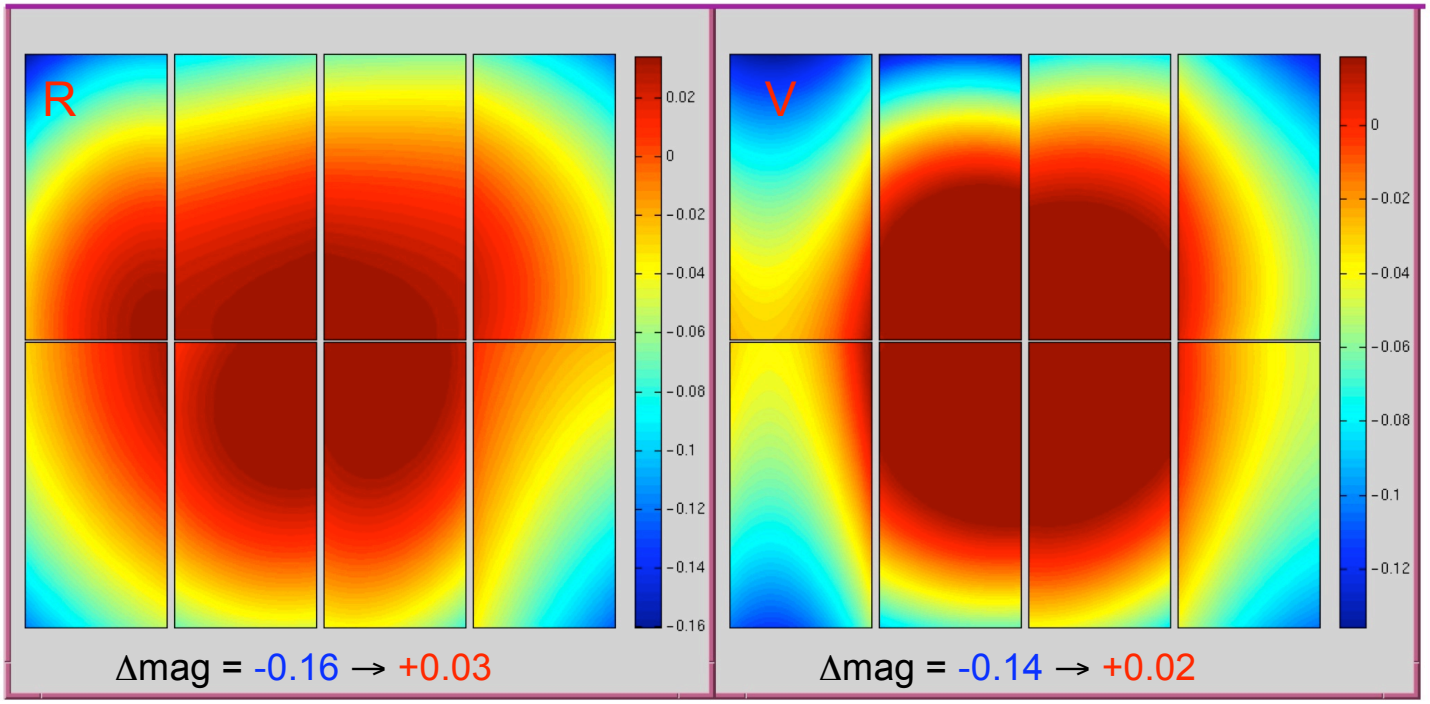
- Due to vignetting and stray light, a detector's response function differs for point sources and extended sources
- Standard flat fields (domes, twilights, skies) may flatten an image sky background well, but not the stellar photometry
- The solution: star flats (Manfroid 1995)
  - offset a field (like an open cluster) multiple times and fit a spatial function to the magnitude differences for matched stars from the different exposures
  - can also just observe a well-calibrated field once (Manfroid 1996)



Koch et al. 2004, ESO WFI star flats based on SDSS Stripe 82 observations (2nd order polynomial fits)

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Global Relative Calibrations: The Global Calibrations Module (GCM)

GCM Zeropoint Solver Code

- Uses matrix inversion algorithm developed by Glazebrook et al. (1994) and used by MacDonald et al (2004).
- Written in Java
- Uses cern.colt.matrix
- **Input:** An ASCII table of all unique star matches in the overlap regions
- **Output:** The ZP offsets to be applied to each field, the rms of the solution, and QA plots

GCM Star Flat Code

- Basic prototype code developed in the SDSS software environment (Tcl/C)
- Future version in Java
- Currently assumes the star flat correction is a purely radial, 3rd order polynomial

For more details, see the talk on Global Photometric Calibration during the Wednesday morning Data Management Breakout Session

Global Absolute Calibration and Final Calibration

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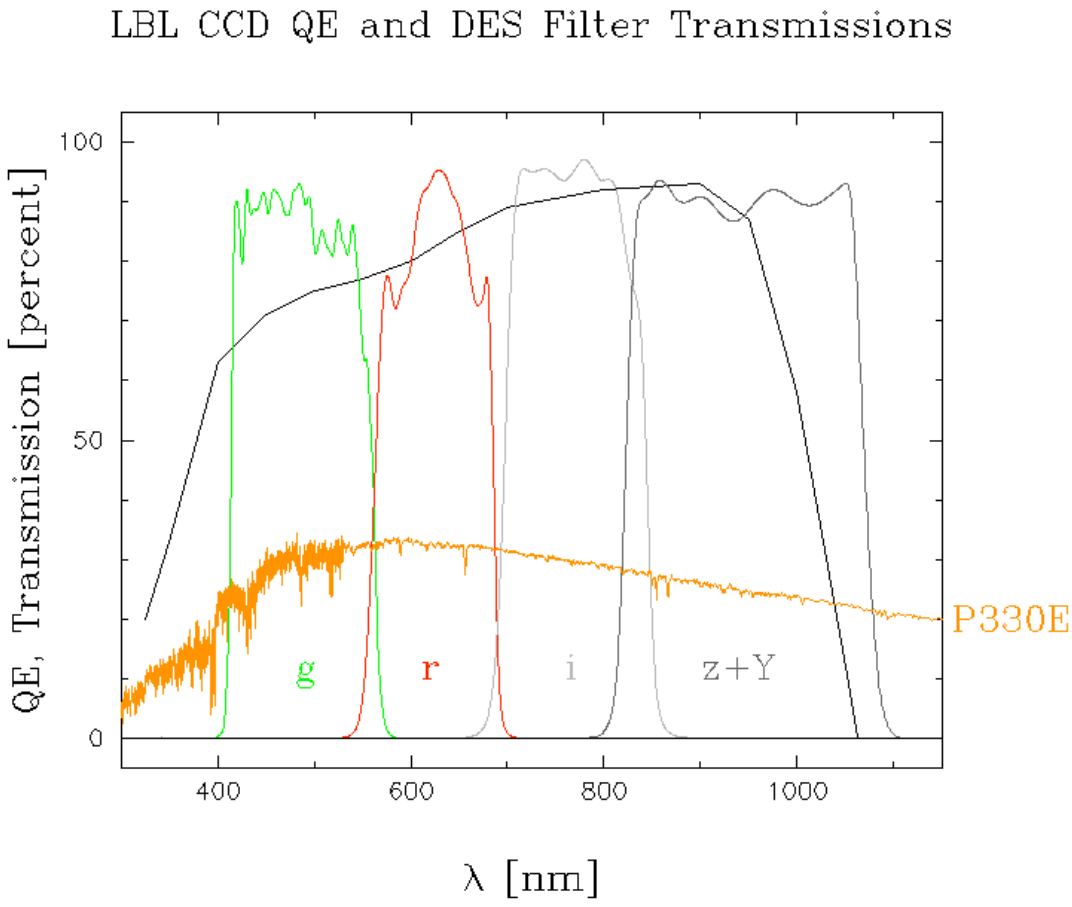
Global Absolute Calibration

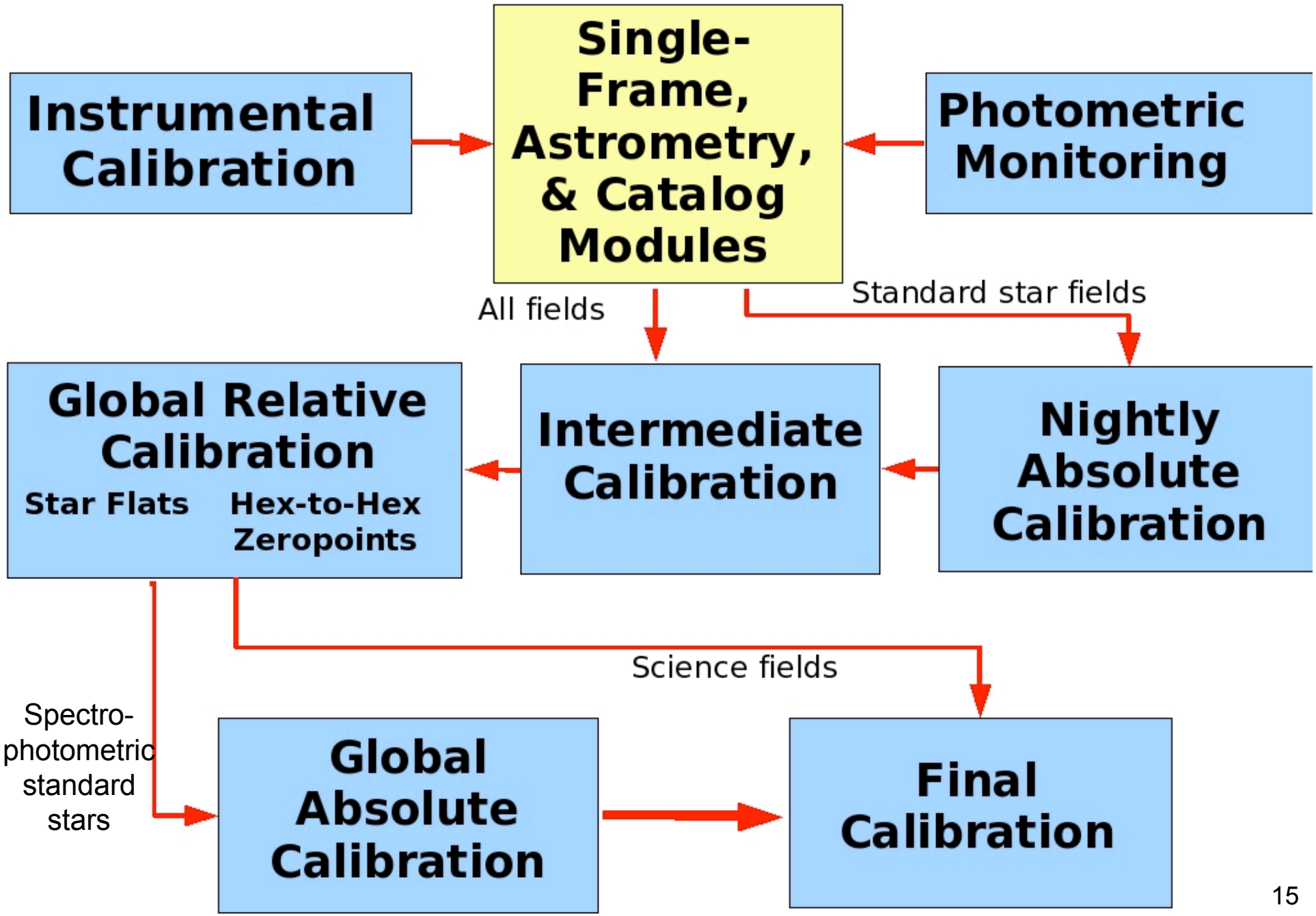
- Compare the synthetic magnitudes to the measured magnitudes of one or more spectrophotometric standard stars observed by the DECam.
- The differences are the zeropoint offsets needed to tie the DES mags to an absolute flux in physical units (e.g., ergs s^{-1} cm^{-2} $Å^{-1}$).
- Absolute calibration requires accurately measured total system response for each filter passband as well as one or more well calibrated spectrophotometric standard stars.

Final Calibration

- Apply the magnitude zeropoint offsets to all the catalog data.



DES Calibrations Flow Diagram (v2)



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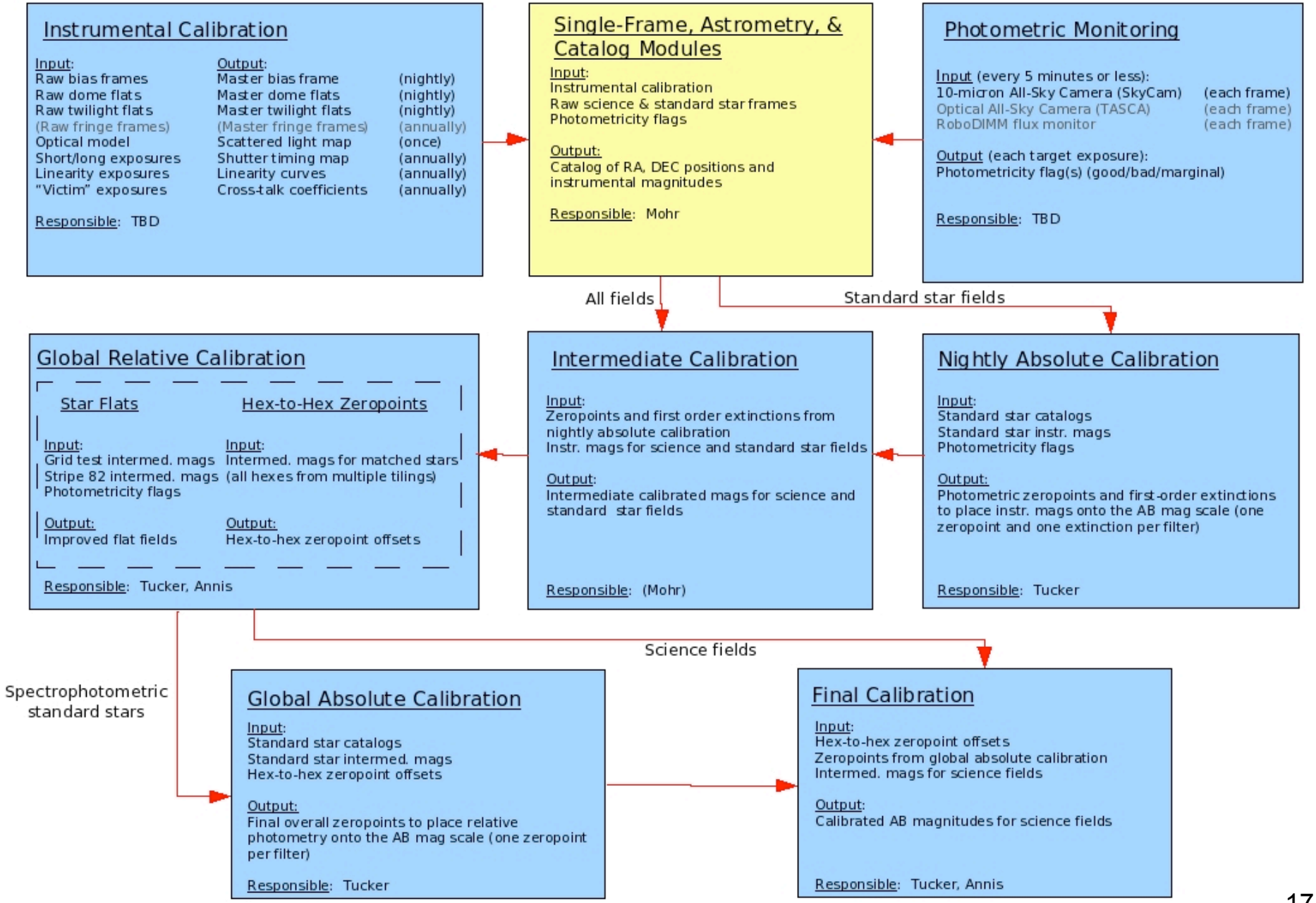
Extra Slides

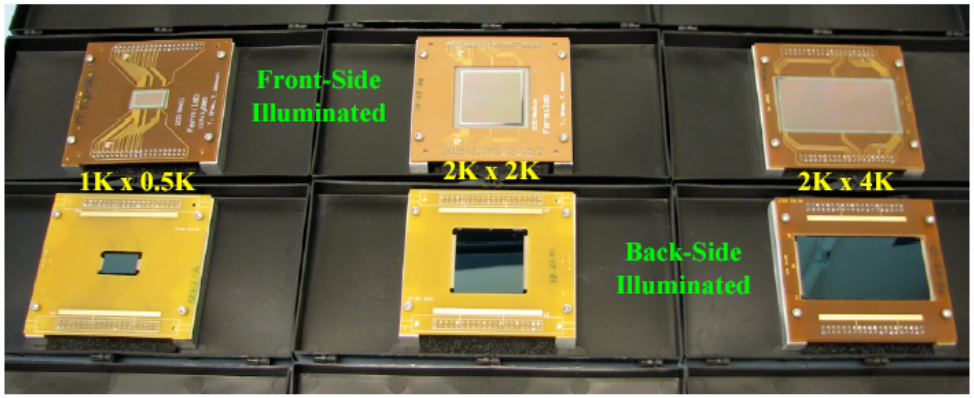
DES Photometric Calibrations Flow Diagram (v2.2)



2008A NOAO Proposal

DARK ENERGY SURVEY

- **Title:** Engineering Tests and Initial Calibration of DECam CCDs
- **PI:** Darren DePoy, **Cols:** Ricardo Schmidt, Douglas Tucker, Brenna Flaugher
- **Telescope:** CTIO SMARTS 1m telescope
- **Instrument:** DECam 2kx2k CCD
- **Filters:** DES g, r, i, z, Z, Y, and a 0.93-0.96μ H_20 absorption feature filter
- **Goals:** on-sky tests and calibration of the DECam CCDs and DES filters, refine definition of DES z/Z and Y filter, initial search and calibration of DES z/Z and Y-band standards
- **Dates:** 9-15 April 2008



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Nightly Absolute Calibration: The Photometric Standards Module

- Written in Java
- Uses the cern.colt.matrix Java classes
- Interacts directly with the database:
  - Queries stars in standard star fields to match with photometric standards
  - Ingests solutions back to database
- Solves for photometric zeropoints ("a_n") and instrumental color term ("b_n") coefficients for all *n* CCDs simultaneously:

$$m_{inst} - m_{std} = a_1 + \ldots + a_{62} + b_1 \times (color - color_0) + \ldots + b_{62} \times (color - color_0) + kX$$

  - Option to set k to a fixed value rather than to solve for it
  - Option to set all b_n's to a single fixed value rather than to solve for them
- Outputs QA plots of the fits to the photometric solution.
- Tested in Data Challenges 1, 2, and 3
- Is a nearly finished product
  - Still need to implement the option ability to fix individual photometric zeropoints ("a_n") and/or individual instrumental color term ("b_n") coefficients

Blanco Cosmology Survey, Fixing *b*'s to 0 (rms=0.041 mag, χ^2/ν=4.24)

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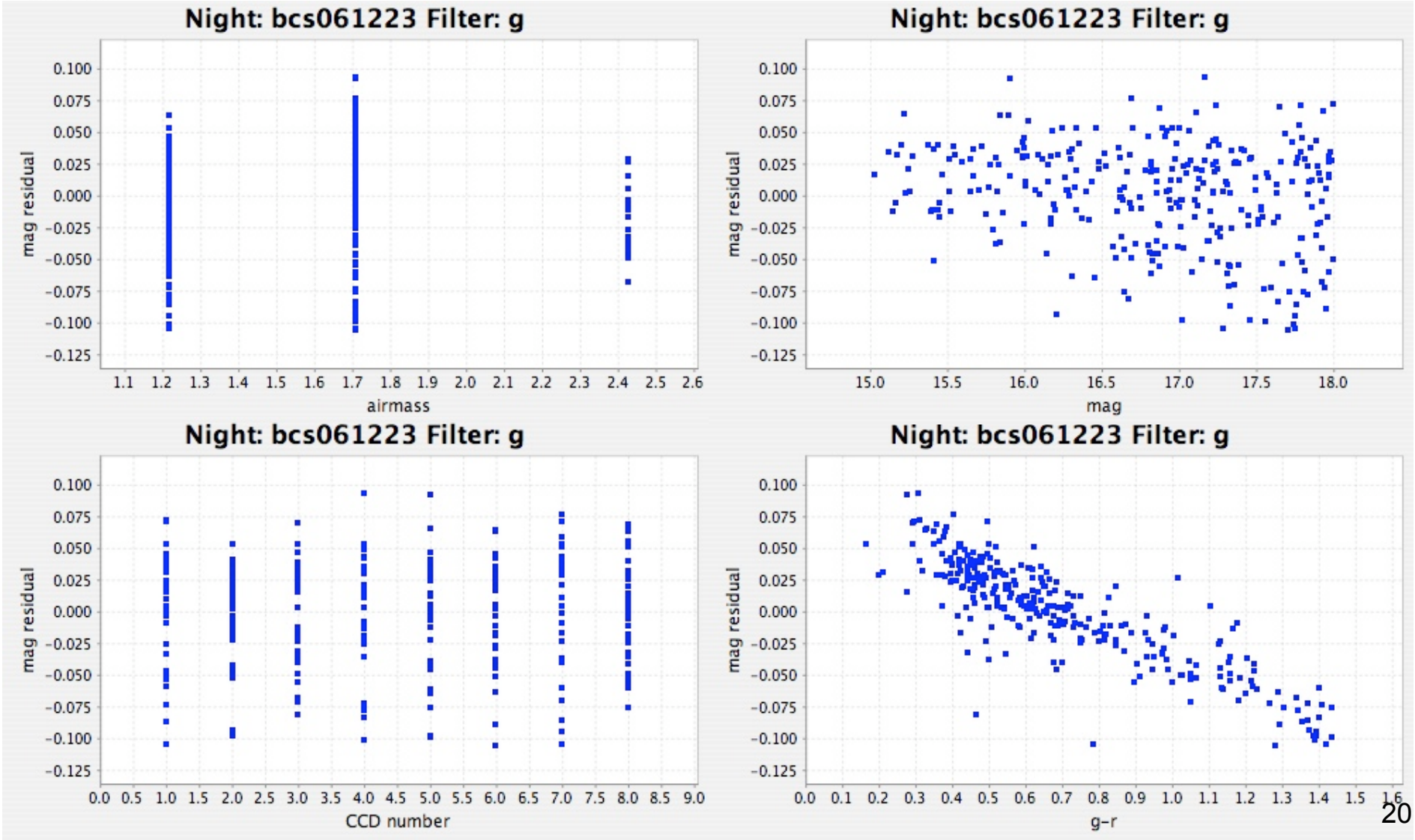

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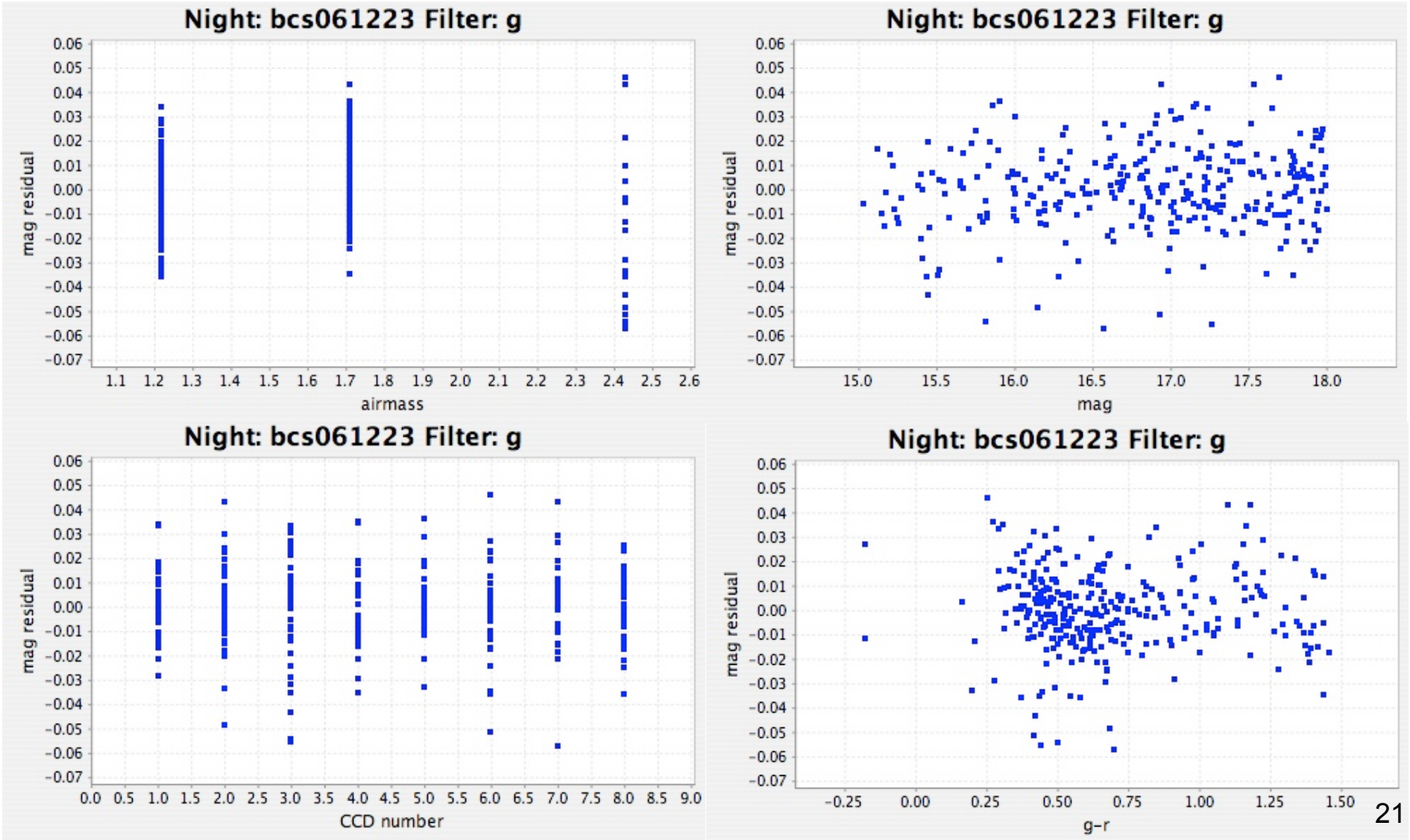

Global Relative Calibrations: Simulation

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INSTRUMENT MODEL:

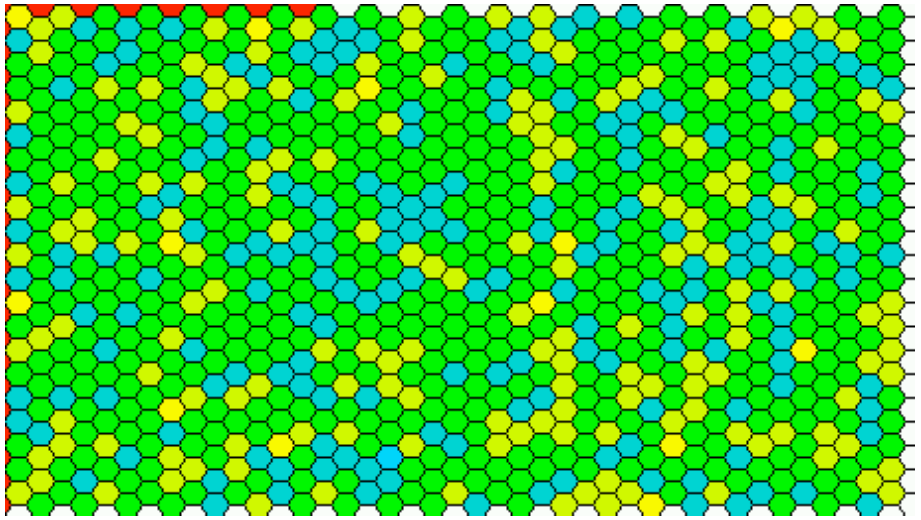
A multiplicative flat field gradient of amplitude 3% from east to west

An additive scattered light pattern with a amplitude from the optical axis, 3% at the edge of the camera

An additive 3% rms scattered light per CCD

Solution:

- Simultaneous least squares solution to the underlying relative photometry given the observations



scaling bar is –0.20 mags to +0.20 mags

Relative Calibration	
Tiling	σ (rms of hex ZPs)
1	0.035
2	0.018
5	0.010

Global Calibration Module : Global Relative Calibrations

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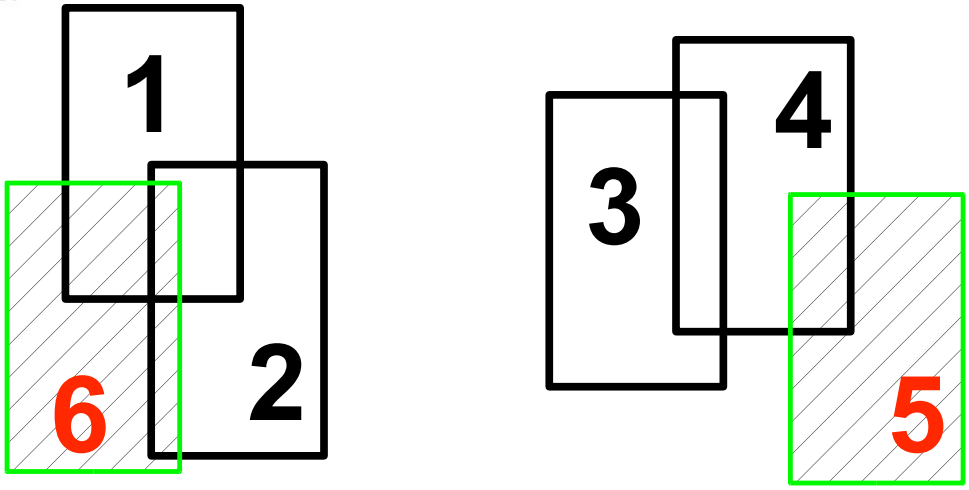

Example:
Frames 5 & 6 are calibrated.
The others are uncalibrated.

- Method used by Oxford-Dartmouth Thirty Degree Survey (MacDonald et al. 2004)
- Developed by Glazebrook et al. (1994) for an imaging K-band survey

- Consider n frames, of which (1, …, m) are calibrated and (m+1,…,n) are uncalibrated.
- Let $\Delta_{ij} = \langle mag_i - mag_j \rangle_{pairs}$ (note $\Delta_{ij} = -\Delta_{ji}$).
- Let ZP_i be the floating zero-point of frame i, with $ZP_i = 0$ if $i > m$.
- Let $\theta_{ij} = 1$ if frames i and j overlap or if i = j; otherwise let $\theta_{ij} = 0$.
- Minimize $S = \Sigma\Sigma\ \theta_{ij} (\Delta_{ij} + ZP_i - ZP_j)^2$

Global Calibration Module : Global Relative Calibrations

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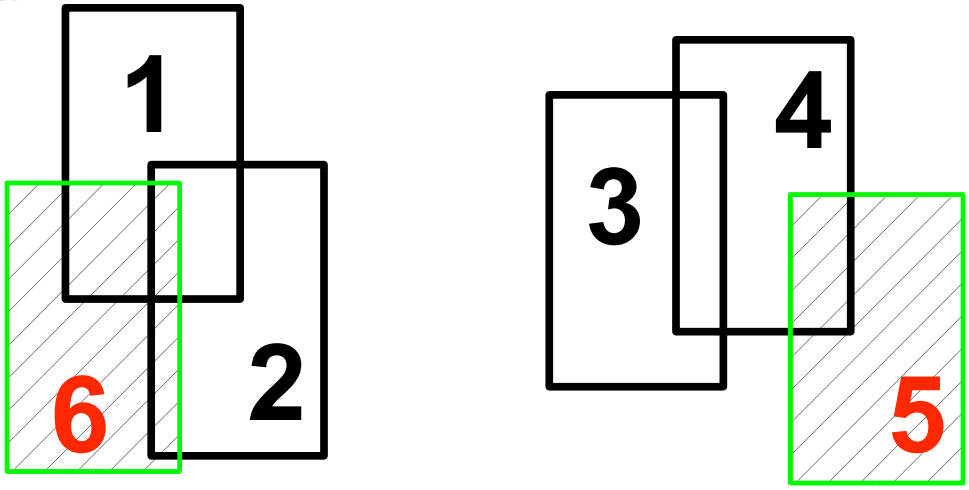

Example:
Frames 5 & 6 are calibrated.
The others are uncalibrated.
(From Glazebrook et al. 1994)

$$\begin{vmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} \times \begin{vmatrix} ZP1 \\ ZP2 \\ ZP3 \\ ZP4 \\ ZP5 \\ ZP6 \end{vmatrix} = \begin{vmatrix} \Delta_{12} + \Delta_{16} \\ \Delta_{21} + \Delta_{26} \\ \Delta_{34} \\ \Delta_{43} + \Delta_{45} \\ 0 \\ 0 \end{vmatrix}$$

Global Calibration Module : Global Relative Calibrations

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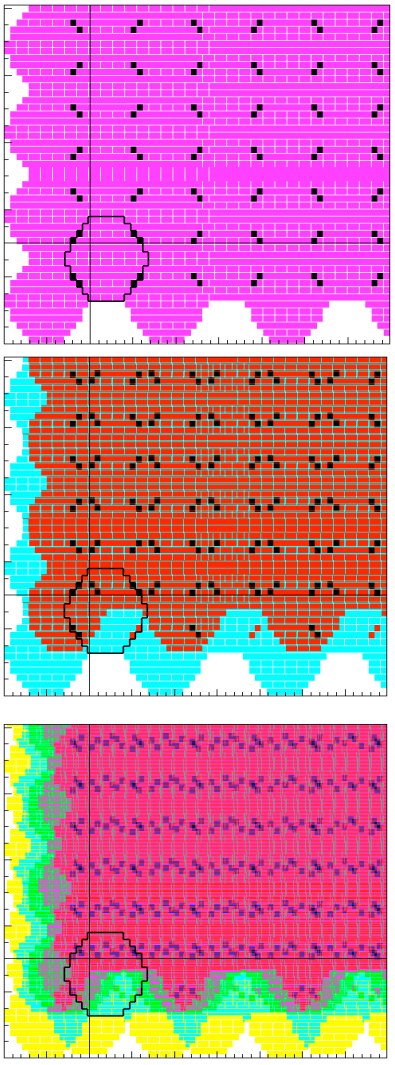

Global Relative Calibrations: Prototype Star Flat Code

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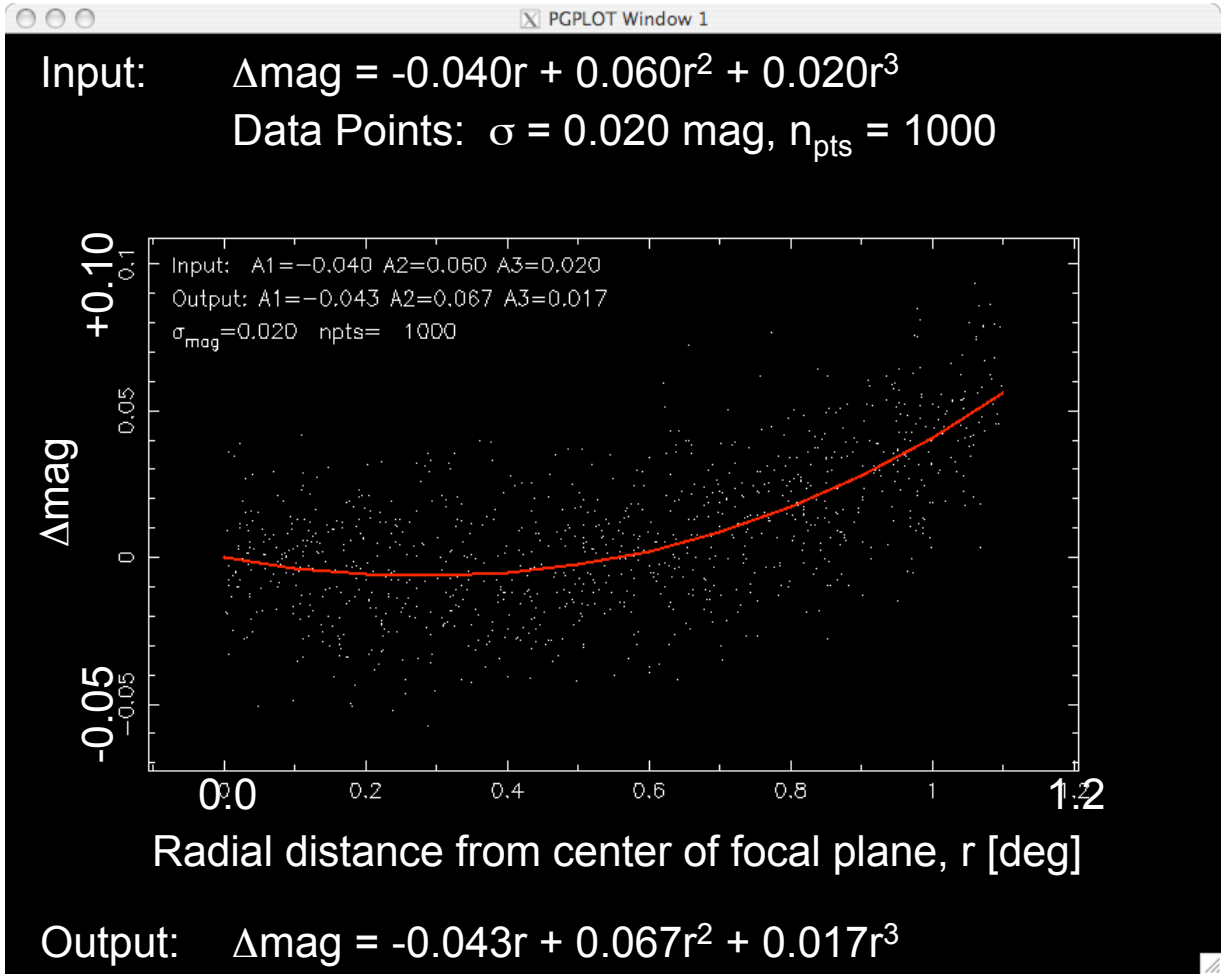

Global Absolute Calibration

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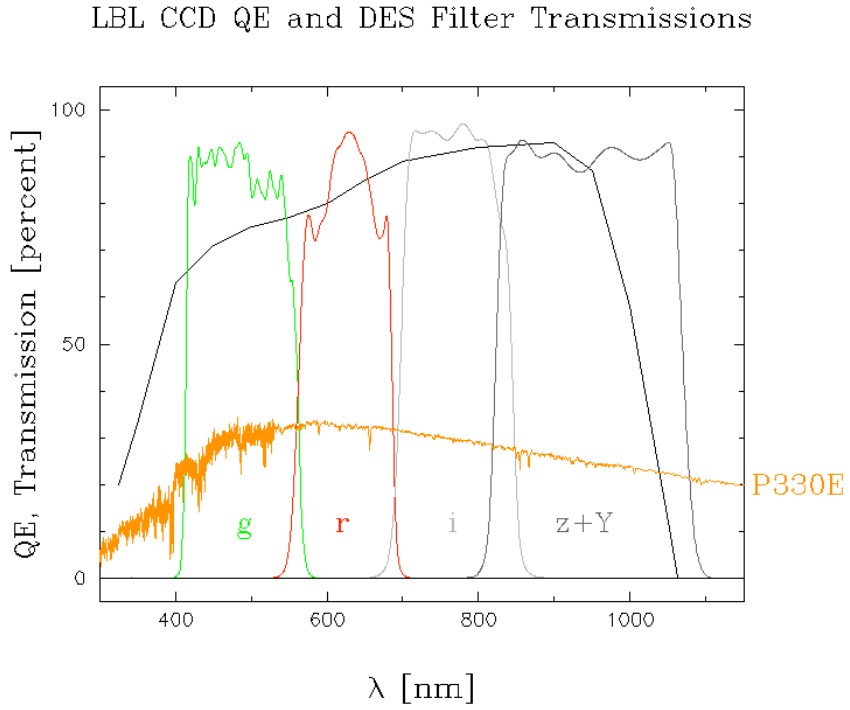
- Need:
  - one or more spectrophotometric standard stars which have been calibrated (directly or indirectly) to a NIST standard source
  - an accurately measured total system response for each filter passband for at least one CCD
    - filter transmissions, CCD QE, optical throughput, atmospheric transmission

- Calculate the expected photon flux F_{exp} for each std star in each filter passband (synthetic photometry)

- Measure the magnitude for each standard star in each filter passband with the Blanco+DECam

- Calculate the zeropoint zp via the relation,

  10**[-0.4*(mag – zp)] = F_{exp}



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Global Absolute Calibration: Spectrophotomeric Standards

- ~100 Hot White Dwarfs (DA) in SDSS Stripe 82 (r=16-21)
  - Need to know temperature and log g for “true” SED (models)
  - Need high-resolution spectroscopy (ground-based) + modelling?
  - These set an absolute color scale

- LDS 749B (DES Fundamental Calibrator?)
  - In SDSS Stripe 82 (RA=21:32:16.24, DEC=+00:15:14.7; r=14.8)
  - In HST CalSpec database (STIS observations + model)
  - Sets the absolute flux scale relative to Vega (i.e., Vega taken as “truth”)

- Others
  - E.g, G158-100, GD50, GD 71, G162-66
  - All are HST WD spectrophotometric standards
  - All are visible from CTIO
  - All are V> 13.0 (won’t saturate DECam at an exposure time of 5 sec (FWHM ~ 1.5”)